Thermal error compensation for large heavy duty milling-boring machines

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Outline

Large heavy duty milling-boring machines

Thermal error management

Thermal Error Compensation System

General considerations

Large heavy duty milling-boring machines

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General considerations

Thermal error management strategies

Temperature control

Minimize temperature variations in the machine

Design for thermal error reduction

Minimize errors at TCP generated by temperature changes

Thermal error compensation

Compensate remaining errors at TCP

Temperature control

Minimize temperature variations in the machine

Heat sources

- Bearings around spindle area
- Ambient temperature, not controlled
- Hydrostatic bearings
- Hot chip falling against machine
- Motors

Cooling units

- Minimize temperature variations, but limited by high required power.
- Dangerous, cooling circuits can be a disturbance source
- Might be too expensive

Main thermal issues

Heavy duty: high heat generation, spindles can rate up to 88kW

Large machine: error amplification with increasing workspace

Applications

Heavy duty milling and boring

Large parts, high precision

Oil&gas, wind energy, aeronautics, etc.

Large machines

Vertical travel up to 8m

Longitudinal travel up to 60m

Multiple spindles/quills with automatic changer

Large machine: error amplification with increasing workspace

Thermal error management strategies

Temperature control

Minimize temperature variations in the machine

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Design for thermal error reduction

Minimize errors at TCP generated by thermal changes in the machine

Application of precision design principles
  Machine design is focused on stiffness
  Precision is important, but it comes next

Focus on avoiding bending errors
  Linear errors are ‘easy’ to compensate
  Bending errors are more difficult to compensate at TCP
  Bending errors change tool orientation

Thermal error compensation

Estimate and compensate thermal errors during machine operation

Thermoelastic machine model
  Relate thermal error with temperature field, spindle speed, position in workspace
  Can be based on simulations (FEM) and/or measured data

Implementation
  Experiments/simulations to characterize model
  Simulation model running on CNC/PLC

Impact
  Low-cost solution, big improvements are possible
  Risk of lack of robustness

Thermal Compensation System

Main objectives
  Robust and effective compensation method:
    Improve machine accuracy, never make it worse
  Minimize machine occupation time:
    Fast machine characterization method
    Multiple heads, one 8h shift per spindle head and quill
  Simple to implement
    By machine operator
    Automate the process
  Flexible
    Compatible with main CNC systems
    Full range of machines/spindles/quills

Experimental setup

Software in external laptop
  Data acquisition from CNC/PLC and displacement sensors
  Generate movement program for CNC
  Automatic model fitting
  Automatic generation of compensation tables

Hardware
  Several measuring points within workspace
    - RAM and quill positions
    - Spindle orientations
  Thermally stable measurement targets

Implementation in machine control

Variety of controllers
  Siemens Sinumerik
  Fanuc
  Heindenhain
  Fagor Automation

Data acquisition
  Temperature from embedded sensors
  Machine axis positions

Compensation in CNC/PLC
  Application on CNC PC
  Embedded code in PLC

Compensation results: spindle head

All results are normalized to the maximum measured value
**General considerations**

- Do not be too ambitious. Focus on dominant errors.
  - Smaller effects are more difficult to characterize, and
  - They might affect robustness.

- Compensation model structure:
  - The simpler the better. Improve sensor location before adding complexity.
  - Temperature and machine position as only inputs to the model.

- FE can be useful.
- Improve design and cooling elements (Minimize bending deformations).
- Find optimal sensor location (structural elements, near heat source, near linear scales).
  - Not for compensation, experiments are needed if high precision is required.

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**Careful with cooling systems**

- Keep machine temperature constant, not at 20ºC.
- Discard transient effects.

- Keep in mind industrial feasibility:
  - Minimize machine occupation time.
  - Simple procedure to be implemented by operators.
  - Be aware of control requirements/limitations.

- Special applications with extreme requirements:
  - When possible, re-think the manufacturing steps (CAM).
  - Add many more sensors, use some math tricks (e.g., POD) to find best correlating ones.
  - Take time to properly characterize the effect of ambient temperature.

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**Thank you!**